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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Dr. Kwon's group achieved the main technical goal of the proposed research by demonstrating the applicability of variable temperature scanning laser microscopy (VTSLM) in coated conductor diagnosis. In the first year, they set up VTSLM, computerized instrument control, investigated epitaxial films, and corroborated the validity of VTSLM measurements. The major accomplishments of the second year are the development of image processing computer programs to obtain the spatial map of superconducting transition temperature and current distribution as well as obtaining such maps in coated conductors. During the last year, more new results were obtained showing the qualitative differences between IBAD and RABITS coated conductors and establishing a correlation between VTSLM image and local superconducting dissipation.

15. SUBJECT TERMS

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1. Cover Sheet

Final Performance Report

(project period 08/01/01-12/31/04)

Principle Investigator's name: Chuhee Kwon, Ph.D.

Institution's name: California State University Long Beach

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Agreement number: F49620-01-1-0493

Title of Project: Development of Variable Temperature Scanning Laser Microscope for Diagnosing Coated Conductors

2. Objectives

Objectives of the research program are (1) to develop variable temperature scanning laser microscope (VTSLM) and optimize the operation for coated conductors and (2) to investigate a room temperature signature for local non-uniformities.

Objectives of the education program are (1) to provide year-round research scholarships for undergraduate and graduate students, (2) to establish the summer Physics research program with nearby community colleges, and (3) to support travels for students to participate research conferences.

3. Status of Effort

We achieved the main technical goal of the proposed research by demonstrating the applicability of variable temperature scanning laser microscopy (VTSLM) in coated conductor diagnosis. In the first year, my group set up VTSLM, computerized instrument control, investigated epitaxial films, and corroborated the validity of VTSLM measurements. The major accomplishments of the second year are the development of image processing computer programs to obtain the spatial map of superconducting transition temperature and current distribution as well as obtaining such maps in coated conductors. During the last year, more new results were obtained showing the qualitative differences between IBAD and RABITS coated conductors and establishing a correlation between VTSLM image and local superconducting dissipation. The scientific impact of this research program could be measured in terms of renewed interest in various scanning laser microscope techniques from other groups in the world.

In education aspect, I ran three consecutive years of successful summer research program for community college students, and supervised seven undergraduate and seven graduate students in research. Four students went to PhD program and three students are currently working in high technology companies including Northrop Grumman and Aerospace Corporation.

4. Accomplishments/New Findings

Experimental Setup

Figure 1 shows (a) a schematic diagram and (b) a photograph of our experimental setup. A helium-Neon laser between 5 mW and 20 mW is used, and the laser beam is modulated around 1 KHz by a standard mechanical chopper or an acousto-optic chopper. The laser beam is coupled into an optical fiber and focused on the surface of the film by an objective lens (x10, x20, or x50). The fiber and lens assembly is fastened to a three-axis movable stage system which scans the laser beam on the surface of a sample in both horizontal and vertical directions.

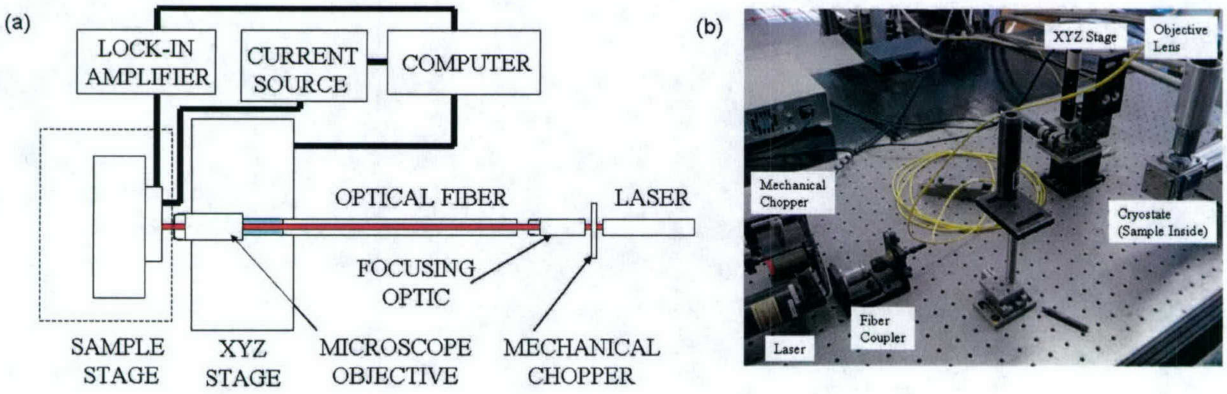

Figure 1 (a) Schematic diagram of our experimental set up. (b) Photograph of the set up.

The measurement is performed using a four-probe geometry under a dc bias current (I_{dc}). Since the laser acts as a local heating source, it generates ac voltage (δV) resulting from the local change of resistance (critical current) in the case of VTSLM (LTSLM). The ac voltage data are acquired by a lock-in amplifier with respect to the position of laser beam using a homemade Labview program. The ac voltage data are transformed into images by a commercial software. The temperature of the film is controlled by a cryogenic system of cryostat and a temperature controller.

While δV image is acquired, the intensity of reflected laser beam is also recorded using the photo-diode with respect to the laser beam position. Figure 2 is a photo-diode image of a micro-chip. The 0.5 μm step image shows that the spatial resolution of our set-up is about 1 μm or better.

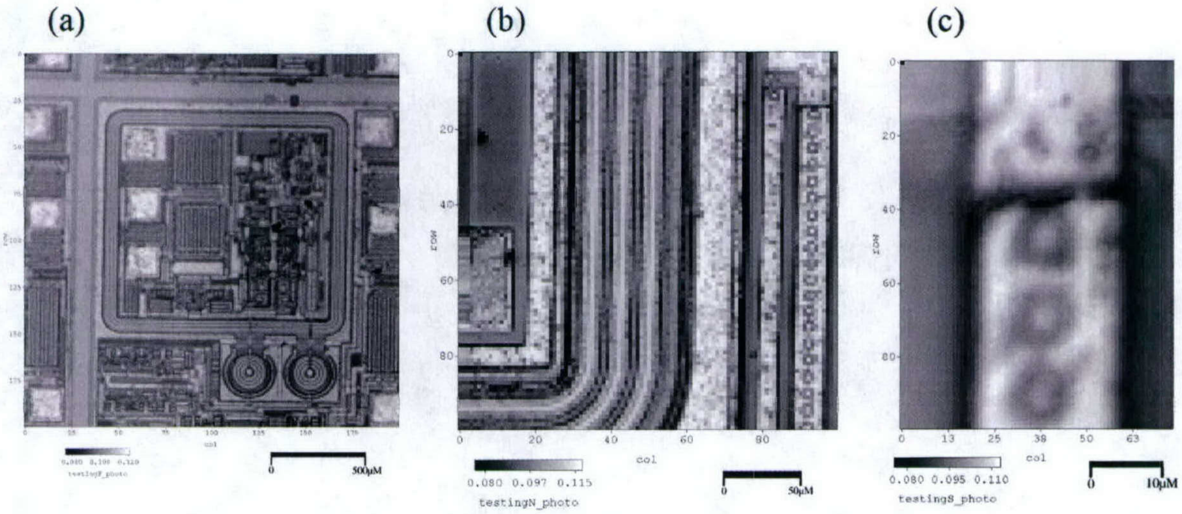

Figure 2. Photodiode images of a micro-chip. (a) An image of a whole chip taken with 10 μm steps, (b) an image of a small area taken with 2.5 μm, and (c) with 0.5 μm.

Summary of SLM Technique

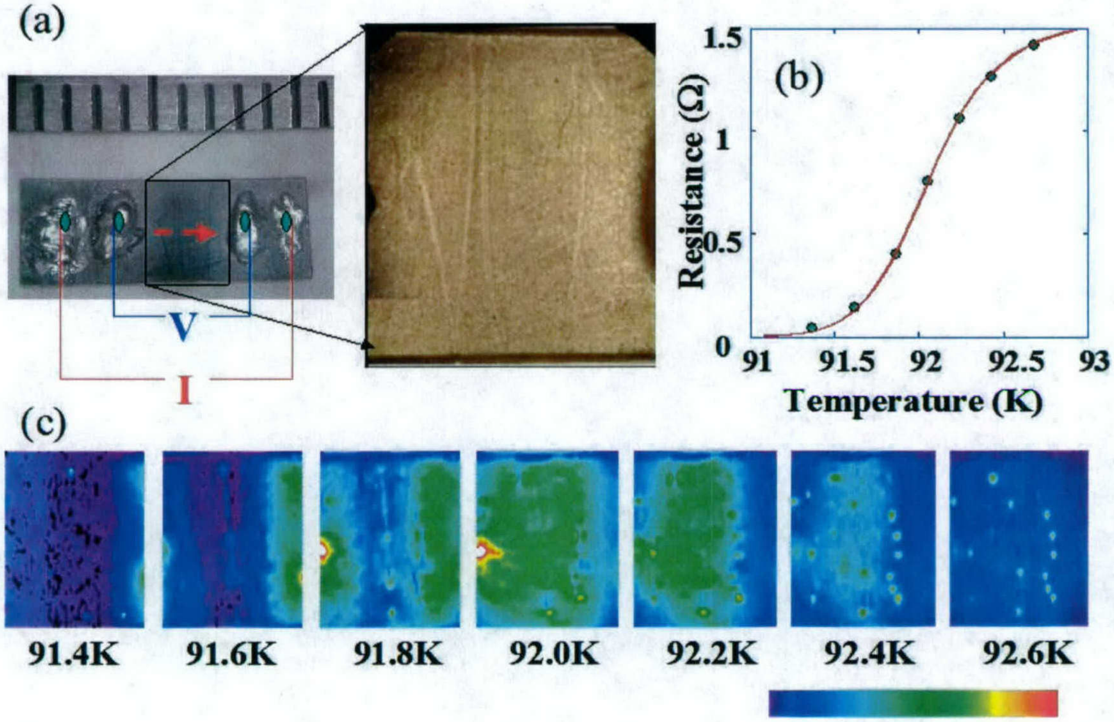

Figure 3 (a) A photograph of the sample showing the measurement geometry. (b) Resistive transition of the sample. (c) A series of VTSLM images taken near the transition temperature.

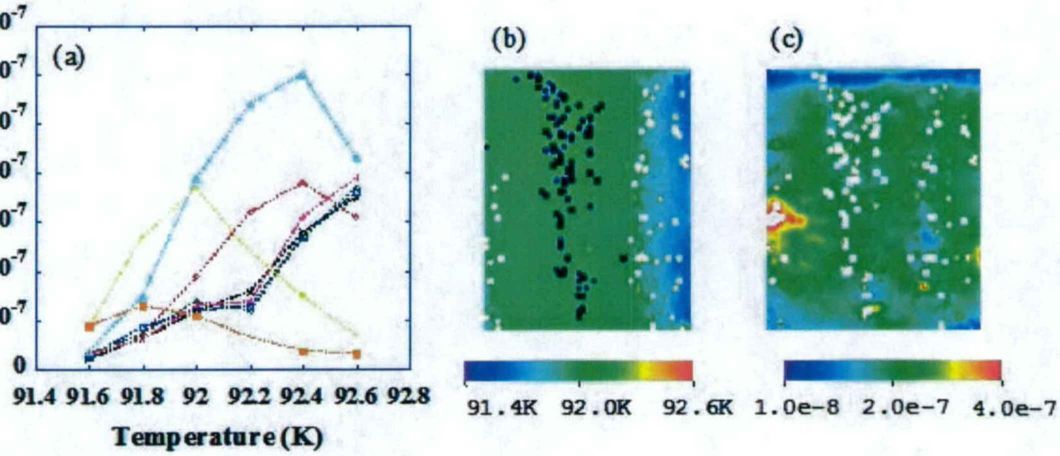

Figure 4 (a) dV versus temperature for several points in Fig. 3 (c). (b) T_c^* and (c) δV_{max} maps obtained from Fig. 3(c) using the homemade program.

In this section, I will summarize various images we use to understand and to analyze samples. For VTSLM images, we take a series of images near the superconducting transition temperature. Figure 3 shows (a) a picture of an IBAD sample and the measurement geometry, (b) resistive transition, and (c) a series of VTSLM images from the sample. Figure 4 (a) is a plot of temperature versus δV for several points in Fig. 3(c) images. As expected, most points have a peak response in this temperature range. A homemade Mathematica program selects the peak temperature (T_c*) and the maximum voltage (δV_m) from each point and the resulting image of T_c* and δV_m is shown in Fig. 4 (b) and (c). We obtain the degree of spatial non-uniformity in T_c from Fig. 4(b). We have also realized δV_m is loosely related to the local current density, even though the relationship is not straightforward because the current rearranges in 2-dimension during the local laser heating. In order to understand the relationship, we have developed VTSLM simulation program based on Kirchoff's laws.

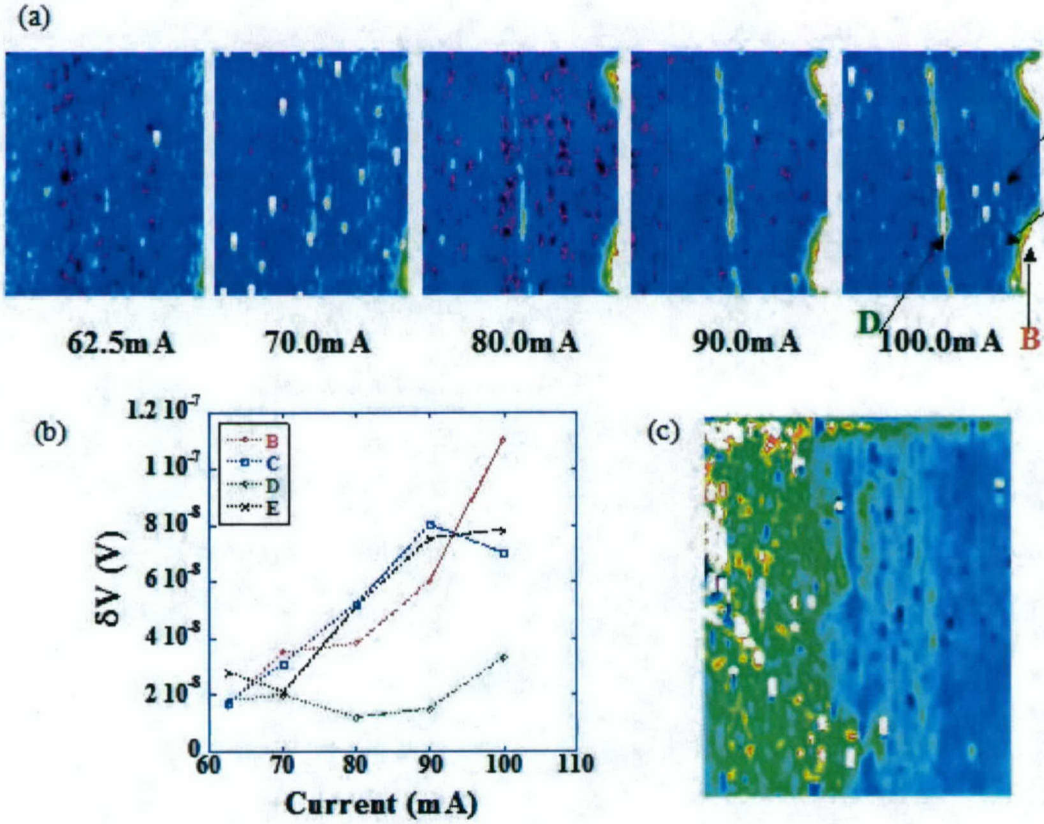

Figure 5 (a) A series of LTSLM measured at 90.0 K. (b) δV versus dc bias current for several points in Fig. 5(a). (c) I_c maps obtained from Fig. 5(a).

The similar measurement is performed in the superconducting state and it is called low temperature scanning laser microscopy (LTSLM). In LTSLM, the δV represents a local dissipation. Figure 5 (a) is a series of LTSLM images taken with increasing I_{dc}. Figure 5 (b) shows δV vs. I_{dc} for several points in the LTSLM images. The δV increases with I_{dc} indicating the beginning of dissipation in some points, while the point E is still superconducting. By choosing voltage criteria (V_c), in this case we used 5×10^{-8} V, we can determine the local I_c (x, y). Using another homemade Mathematica program, which fits each points to a power low ($V \sim I^{\alpha}$) and finds I_c according to V_c, we can obtain the local dissipation map shown in Fig. 5 (c).

Summary of Accomplishments

1. We have established qualitative differences between RABITS and IBAD CCs in VTSLM.

In 50 μm scanning step images, IBAD samples appear to have more uniform current distribution than RABiTS samples, which can be related to the smaller grain sizes in IBAD. The images of IBAD samples taken with higher resolution reveal feather-like clusters with 40 - 150 μm in diameter. In RABiTS, the shape and size of percolation clusters are clear and do not change between high and low resolution images, and they are estimated to be 50 - 150 μm. VTSLM images prove that the current percolation in the transition region is due to the combination of the grain boundary network and the critical temperature variation. The details can be found in the annual performance report for year ending 2004 and in the publication #8.

2. We find the signature response of current bottleneck in VTSLM and LTSLM images.

We have found that many of low I_c^* areas can be identified in VTSLM images with high δV_{max} and low T_c^*. This result means that low I_c^* areas are formed when an area is forced to carry high current due to various reasons (for example, scratches, grain boundary percolative network, and patterned geometry, etc) and the increased current density is large enough to cause the reduction of T_c^*. The details are reported in the annual performance report for year ending 2004 and in the publication #8 and #9.

3. We have demonstrated that SLM can play a critical role in studying striated samples.

We have showed that striations are doing what they are designed to do, i.e. (a) act as artificial barriers (b) allow current crossing between filaments via bridges. In brick-wall pattern samples, the dissipation begins around the bridge area, possibly due to the damage caused during the processing. We also find the zipper area is susceptible to the current crowding, due to the disabled filaments in either side. The details can be found in the annual performance report for year ending 2004 and in the publication #7 and #9.

4. We developed several computer programs for data analysis as well as for the simulation of VTSLM image.

The T_c* and δV_m maps are obtained from VTSLM images as shown in Fig. 4. Also the dissipation map can be obtained from LTSLM images as in Fig. 5. We are continuously developing the simulation program for VTSLM images. The details for the VTSLM simulation can be found in the publication #3, the annual performance report for year ending 2003, and the annual program review presentation given in Jan. 2005.

Summary of Student Theses

The support of this research program has yielded three masters theses by S. Seo, M. Price, and K. Waller.

S. Seo's thesis was to develop and to prove the concept of VTSLM. The main result of thesis is published in Seo *et al.* (2002). Using a patterned YBCO film, she measured δV (x, y) near the superconducting transition temperature and demonstrated that there were spatial non-uniformities in T_c as well as δV. She also measured the laser beam diameter using a knife-edge technique.

M. Price developed a Mathematica program for extracting local critical temperature and maximum voltage response from a series of VTSLM images. This program interpolates δV data at different temperatures for a given position of the film and evaluates δV_m and T_c^* at the point. By applying this interpolation throughout the film, a distribution of δV_m and T_c^* in the film can be mapped. A noise level threshold was chosen such that any data not exceeding that threshold would be zero. When this data is fitted by the program, the temperature difference between the fitted peak and measured peak is about ±0.1K. Wang *et al*'s Physica C (2004) shows the comparison of δV vs. temperature between the continuous measurements and data taken from VTSLM images. He also measured superconducting MgB_2 films, but did not observe any significant spatial non-uniformity in T_c.

K. Waller's thesis was to compare the differences between IBAD and RABiTS coated conductors. She observed that in an IBAD sample, more features are resolved with decreasing scanning step size and the current flows throughout entire sample. On the other hand in a RABiTS sample, the features remain the same regardless of scanning step size and the large grain seems to affect the current flow. Her work became the basis for further measurements and the IEEE paper by Wang *et al.* (2005).

5. Personnel Supported

PI: Chuhee Kwon, Ph.D.
Postdoc: L. B. Wang, Ph.D.
Graduate student: S. Seo, M. Price, K, Waller, S. Yoo, C. Khanal, D. Grant, and K. Barraca.
Undergraduate student: J. Rosales, A. Forrester, J. Mahoney, J. Young, D. Garcia, H. Ku, and F. Esguerra

6. Publications

1. "Spatial Distribution Analyses of Superconducting Transition Temperature in Epitaxial $YBa_2Cu_3O_7$ Film Using Variable Temperature Scanning Laser Microscopy", S. Seo, C. Kwon, B. H. Park, and Q. X. Jia, Mat. Res. Soc. Proc. 689, E8.22.1 (2002).
2. "Imaging Transport Current Distribution in High Temperature Superconductors Using Room Temperature Scanning Laser Microscope", C. Kwon, B. E. Klein, S. Seo, B. H. Park, and Q. X. Jia, Mat. Res. Soc. Proc. 689, E8.35.1 (2002).
3. "Imaging Transport Current Distribution in High Temperature Superconductors Using Room Temperature Scanning Laser Microscope", B. E. Klein, S. Seo, C. Kwon, B. H. Park, and Q. X. Jia, Rev. Sci. Inst. 73, 3692 (2002).

4. "Spatial Distribution Analyses of Critical Temperature in Epitaxial Y-Ba-Cu-O Film Using Variable Temperature Scanning Laser Microscopy", C. Kwon, L. B. Wang, S. Seo, B.H. Park and Q.X. Jia, IEEE Transactions on Applied Superconductivity 13, 2894 (2002).
5. "Variable Temperature Scanning Laser Microscopy of Wider Width High Temperature Superconducting Films" L. B. Wang, M. B. Price, C. Kwon, and Q. X. Jia, IEEE Transactions on Applied Superconductivity 13, 2611 (2003).
6. "Observation of Nonuniform Current Transport in Eptiaxial $YBa_2Cu_3O_{7-x}$ Film Near the Superconducting Transition Temperature", L. B. Wang, M. B. Price, J. L. Young, C. Kwon, T. J. Haugan, and P. N. Barnes, Physica C, **405**, 240-244 (2004).
7. "Mapping the Current Distribution in YBCO Thin Films with Striations", Physica C **419**, 79 (2005).
8. "The Distribution of Transport Current in the YBCO Coated Conductor with Zipper Striations", L. B. Wang, P. Selby, C. Khanal, George Levin, Timothy J. Haugan, Paul N. Barnes, and C. Kwon, accepted to IEEE Transactions on Applied Superconductivity (2005).
9. "Investigation of Current Percolation Characteristics in Coated Conductors", L. B. Wang, G. You, K. R. Barraca, K. Waller, J. M. Mahoney, J. L. Young, and C. Kwon, accepted to IEEE Transactions on Applied Superconductivity (2005).

7. Interactions/Transitions

a. Participation/presentation at meetings, conferences, seminars, etc.

1. Poster presentation at Materials Research Society Fall meeting at Boston, MA, S. Seo, C. Kwon, B. H. Park, and Q. X. Jia, "Spatial Distribution Analyses of Superconducting Transition Temperature in Epitaxial $YBa_2Cu_3O_7$ Film Using Variable Temperature Scanning Laser Microscopy", (Nov. 25 - 30, 2001).
2. Poster presentation at Materials Research Society Fall meeting at Boston, MA, C. Kwon, B. E. Klein, S. Seo, B. H. Park, and Q. X. Jia, "Imaging Transport Current Distribution in High Temperature Superconductors Using Room Temperature Scanning Laser Microscope", (Nov. 25 - 30, 2001).
3. Give a presentation at Air Force Office of Scientific Research Program Review organized by Dr. H. Weinstock, C. Kwon, "Scanning Laser Microscopy of YBCO", Stanford University, Palo Alto, CA (Oct. 22-23, 2001).
4. Poster presentation at Applied Superconductivity Conference at Houston, TX, C. Kwon, L. B. Wang, S. Seo, B.H. Park and Q.X. Jia, "Spatial Distribution Analyses of Critical Temperature in Epitaxial Y-Ba-Cu-O Film Using Variable Temperature Scanning Laser Microscopy", (Aug. 4-9, 2002).
5. Poster at Applied Superconductivity Conference at Houston, TX, L. B. Wang, M. B. Price, C. Kwon, and Q. X. Jia, "Variable Temperature Scanning Laser Microscopy of Wider Width High Temperature Superconducting Films", (Aug. 4-9, 2002).
6. Poster at Student Research Symposium 2002 sponsored by Student Access to Science (SAS) center, J. Young, A. Garcia, M. Price, and C. Kwon, (Aug. 24, 2002).

7. C. Kwon, "Variable Temperature Scanning Laser Microscopy; a Novel Tool for Investigating Local Transport Properties", Colloquium at the Department of Physics and Astronomy, California State University Los Angeles (Oct. 3, 2002).
8. C. Kwon, "Scanning Laser Microscopy", Invited presentation at Air Force Office of Scientific Research Program Review, St. Petersberg, FL (Jan. 2003).
9. C. Kwon, "Scanning Laser Microscopy", Colloquium at the Department of Physics and Astronomy, California State University Long Beach (Feb. 10, 2003).
10. C. Kwon, "Study of Local Current Transport in Coated Conductor Using Variable Temperature Scanning Laser Microscopy", Invited presentation at the 13th Korean-American Scientists and Engineers Association South-Western Region, Cerritos, CA (March 1, 2003).
11. Talk at American Physical Society meeting at Austin, TX, L. B. Wang, C. Kwon, W. Jo, R. H. Hammond, M. R. Beasley, "Spatial Distribution of Critical Temperature and Critical Current in YBba2Cu3O7 Coated Conductors", (March 3 - 7, 2003).
12. Talk in 2003 CSULB Student Research Competition, Jorge Rosales and C, Kwon, "Beam Diameter Measurements" (March 2003).
13. Attended MURI Workshop on Key Scientific Issues for Coated Conductors, University of Wisconsin-Madison (June 11 – 12, 2003).
14. C. Kwon, "Scanning Laser Microscopy", Colloquium at the Department of Physics and Astronomy, California State University Long Beach (Oct. 2003).
15. J. Rosales, an undergraduate student, presented a poster to Sigma Xi Student Research Conference in Los Angles (Nov. 2003). The title of the presentation is "Atomic Force Microscopy Insulin Fibril Formation Study".
16. J. M. Mahoney, an undergraduate student, presented a poster to Sigma Xi Student Research Conference in Los Angles (Nov. 2003). The title of the presentation is "Computer Simulation of Variable Temperature Scanning Laser Microscopy".
17. C. Kwon, "Scanning Laser Microscopy", Invited presentation at Air Force Office of Scientific Research Program Review, St. Petersberg, FL (Jan. 2004).
18. J. Mahoney, an undergraduate student I supervised, won the first place in 2004 CSU-wide Student Research Competition. The title of the presentation is "Computer Simulation of Variable Temperature Scanning Laser Microscopy".
19. Poster at Student Research Symposium 2004 sponsored by Student Access to Science (SAS) center, F. Esguerra and C. Kwon, "Current Distribution Simulations of the variable temperature scanning laser microscopy".
20. Talk in Applied Superconductivity Conference at Jacksonville, FL, L. B. Wang, P. Selby, C. Khanal, George Levin, Timothy J. Haugan, Paul N. Barnes, and C. Kwon, "The Distribution of Transport Current in the YBCO Coated Conductor with Zipper Striations" (Oct. 4 – 8, 2004).
21. Poster presentation in Applied Superconductivity Conference at Jacksonville, FL, G. You, L. B. Wang, K. R. Barraca, K. Waller, J. M. Mahoney, J. L. Young, and C. Kwon, "Investigation of Current Percolation Characteristics in Coated Conductors" (Oct. 4 – 8, 2004)

8. New Discoveries, Inventions, or patent disclosures

None

9. Honors/Awards

None